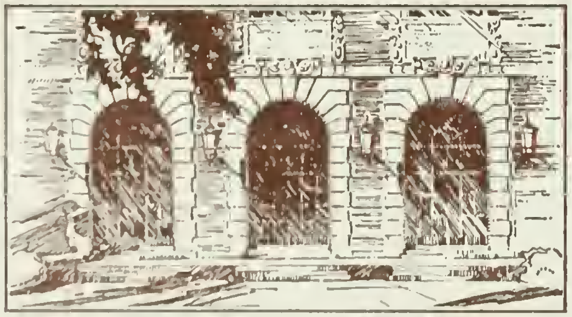

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EXPERIMENTS WITH AN IMAGE PROCESSING COMPUTER

by

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EXPERIMENTS
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IMAGE PROCESSING COMPUTER

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TABLE OF CONTENTS

LIST OF FIGURES

1. IMAGE PROCESSING PROPOSAL

Picture Processing Strategy

Strategy is proposed to permit personnel (not trained in computer technology) to input scanning instructions directly to the image processing system. Cartoons of sample pictures are used to define a training set. Continues work presently underway. (Section 2)

Plane Parallel Processing Strategies

It is our intention here to devise, implement and evaluate parallel processing strategies appropriate to the Pattern Articulation Unit of the Illiac III computer. Procedures to be investigated are: 1) shape determination from scenes of shaded objects, 2) fast articulation of (quasi) line-like images, and 3) detection of differential changes in scene representation with motion. (Section 3)

List Processing in Taxicrinic Processors

The appropriateness of the Taxicrinic Processors of Illiac III as a vehicle for the implementation of list processing languages will be evaluated. The class of features peculiar to this processor include: virtual addressing, operand and pointer stacks, hardware implementation of available space, list instructions and the ability to execute a class of procedure calls entirely in hardware. (Section 4)

Applications

In depth investigation will be made of Scanning Electron Microscope (SEM) photographs of polycrystalline and biological materials as a variant of scene analysis. Use of multiple modes (emissive, conductive and luminescent) of the SEM to give multi-spectral description of scene will be probed. Possible application to radiation damage and materials research are contemplated. Liaison with the AEC supported Materials Research Laboratory (MRL) at Illinois will be established. (Section 5)

2. PICTURE PROCESSING STRATEGY

2.1 Research Goal

The object of this research is the development of a strategy to permit personnel (not trained in computer technology) to input scanning instructions directly to the image processing system.

Conceptually we can view this goal as a necessary first step toward the eventual realization of a scanning robot: a machine which given a limited visual environment, and appropriate training, can be said to recognize and describe the objects of its environment with an aptitude approaching that of a trained scanning technician. To approach this ideal, a conventional computer-based image processing system must be augmented by several facilities: (1) Given an appropriately structured learning experience, the augmented system must formulate its own image processing strategy. (2) This strategy, continually guided by evaluative feedback, must provide command and control to the image processing system, and so dictates the frame, orientation, field of view, magnification, etc. of current attention. And (3) the system must provide as output a model of the environment, rather than merely a frame-by-frame image description. This proposal describes strategies, existing image processing equipment and experiments appropriate to explore the potential of a scanning robot.

We observe the computer-based scanning system as conceived here is not intended to produce polished code for the recognition task at hand. Rather the primary role of the image processing package is to establish the feasibility of the scanning task. As attached to a Scanning Electron Microscope (SEM), for example, this system might be directed to determine the distribution of particle parameters, or for polycrystalline materials to estimate for each crystal subpopulation the corresponding surface-to-volume ratio. Alternate graded sets of scanning exercises can be readily devised for other areas of application. The image processing requirements of our users, however, typically embrace both ends of the task spectrum: either (1) the scanning task is variable and short-lived--any quick results (e.g. distribution of particle parameters) would be gratefully received; or (2) the scanning task is extensive and warrants several man years of effort--

were feasibility of the scanning task once demonstrated. It is for these two task situations, viewed exclusively as feasibility experiments, that the design of the automated image analysis system is directed.

2.2 Required Faculties

These faculties must be provided the image processing package:

(1) A programming language to describe the scanning task must be developed. It must be possible to specify the image enhancement, pattern articulation, syntactic analysis (where available) and model construction aspects of the scanning task.

(2) The learning experience, defined in the terms of input cartoons,accompanied by interactive labelling of edges and regions, etc., must be carefully prescribed. The automaton in this way is provided with primitive features to extract and label from test images so that training sets are adequately defined.

(3) The formulation of queries addressed to the scanning supervisor must be possible. For an intelligent automaton must recognize those occasions when its experience is insufficient to cope with new imagery. In this interactive manner the scanning robot can be expected to converge on useful strategies. And finally,

(4) Monitoring capabilities must be provided to evaluate the performance of the automaton and to allow the observer to modify the scanning procedure. Display facilities must include introspective report generation capabilities sufficient to make transparent the invoked current strategy. Should the application later warrant refined design of an optimal scanning strategy, it should then be possible to transfer the accumulated experience of the prototype scanning system.

2.3 Illustration: Use of a Cartoon to Define Preprocessing Tactics

Methodologically, current pattern recognition research as applied to image preprocessing has been negligent in several regards:

1) The scanning task to be performed is often inadequately defined--so the learning task requires undue artificial intelligence.

2) The a priori probability distributions characterizing the signal families to be distinguished are rarely evaluated systematically during the learning experience.

3) Ad hoc preprocessing tactics are often then performed on the picture without any evaluation of what optimal discrimination is inherently possible.

4) An artificial distinction is made between the discrimination of regional attributes, such as texture, and the detection of edges. In fact these techniques are complementary: regions of common attribute (e.g. color, texture, etc.) are circumscribed by edges; and conversely boundaries (edges) can be inferred as the limiting case of "roadlike" areas separating regions of common attribute. To find a cellular mosaic decomposition of the input picture in general requires concomitant use of both techniques.

A new strategy for cellular decomposition, which largely circumvents the above criticism, has recently been developed here and is now undergoing experimental test. In this scheme the human observer prepares the input <u>picture</u> (as an 8 x 10 inch photograph) and its corresponding <u>cartoon</u>: an ink overlay sketch of those edges and by implication, regions the user wishes to have recognized by the automatic image processing facility. (See Figures 1-3). The choice of line width of a cartoon edge reflects the uncertainty in the definition of the corresponding boundary.

After simultaneous photo reduction of the picture and its corresponding cartoon, with care taken to preserve the registry of the two images, the film so obtained is vacuum clamped to the film platten of a S-M-V film transport. These transports, developed originally for bubble chamber data

Polycrystalline Ceramic Fracture Surface

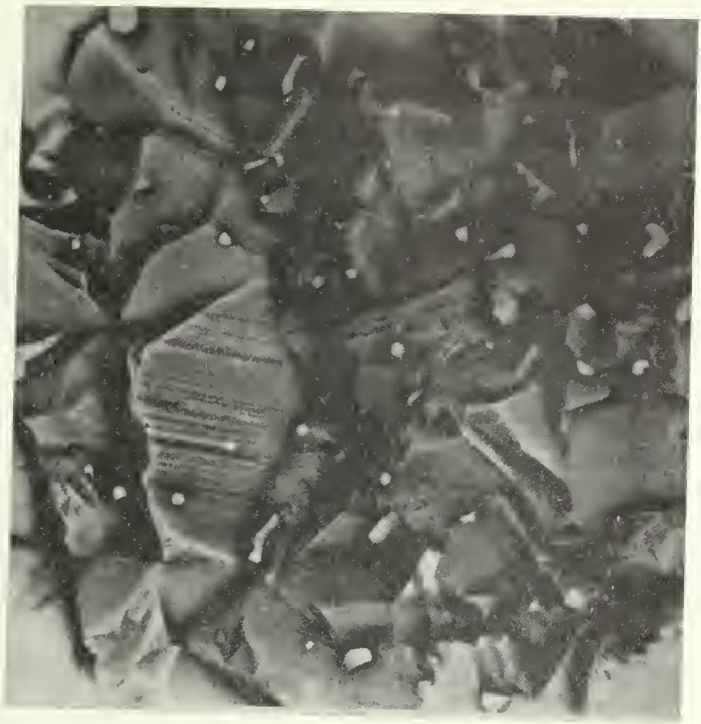


Figure 1

Cilia 22,000X

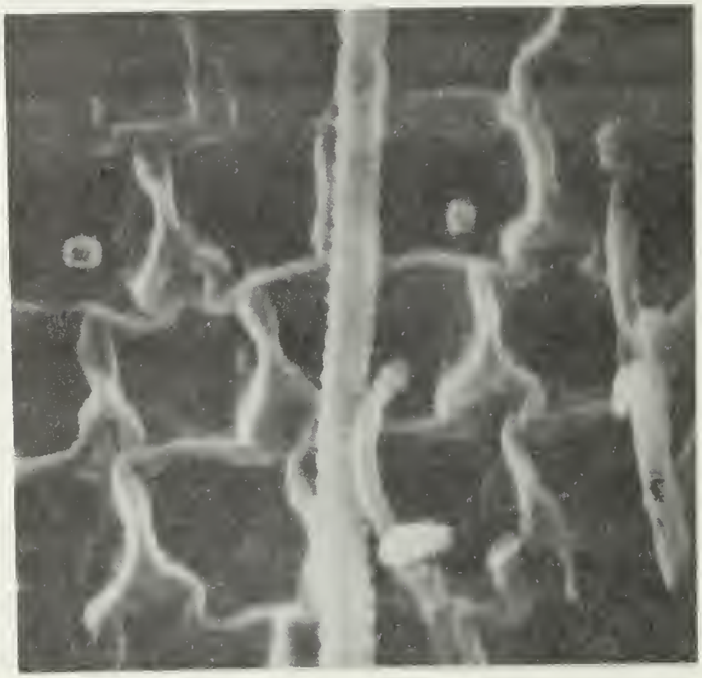


Figure 2

IC Chip Surface 200X

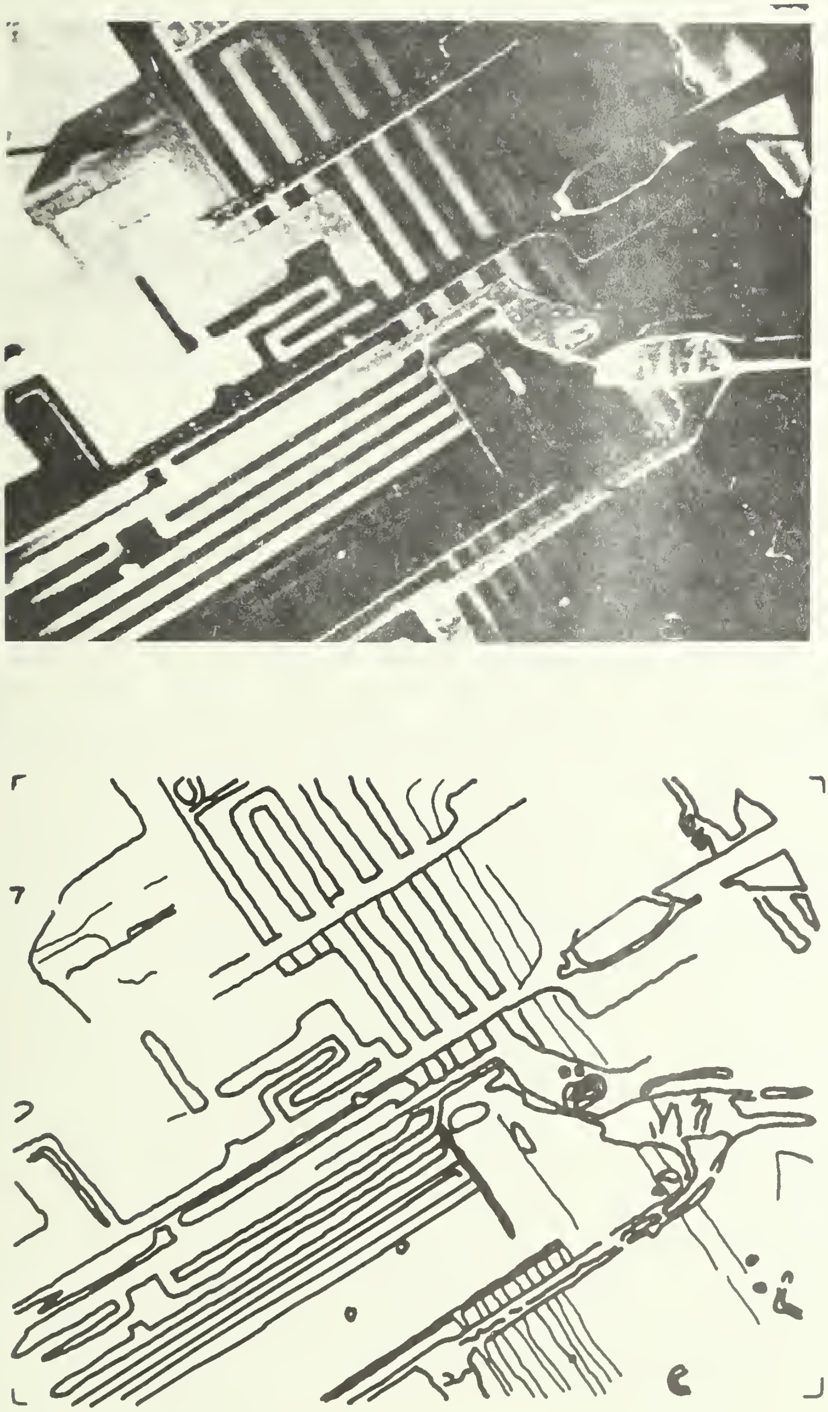


Figure 3

processing, provide a dual position film platten (to accommodate the very long aspect ratio of bubble chamber film) and so allow accurate mechanical translation between the picture and its corresponding cartoon.

The cartoon, of course, can be easily tracked and serves to define a set of edges, which can be then labelled by teletype intervention. In addition the cartoon implies a cellular mosaic decomposition of the image into regions of common attribute: intensity, color or texture--which in turn can be labelled by the human monitor.

Accordingly the cartoon provides an articulation of the test image a training sequence of possible sample points on the cartoon lines (for edge detection) or interior to each enclosed region (for texture discrimination) can be determined. For each such sample point a disc-shaped neighborhood centered about the sample point is defined. The array of gray scale values at each picture element within the neighborhood (i.e. disc about the sampled point) defines a primitive feature vector. Pattern subpopulations, so identified by labelling of the cellular mosaic, can be used to parameterize the pattern classifier--subject to appropriate signal detection theory analysis.

The pattern classifier so determined can then be applied to similar but previously untried pictures. For each such picture a corresponding "cartoon", though now with noise and gaps, is developed. After appropriate refinement this cartoon induces a cellular decomposition of the input image.

2.4 Formal Model for Picture Processing

The object of this research, as asserted above, is contingent upon the development of a formal model for picture processing.

The model emphasizes the global aspects of processing, i.e. some preprocessing is done on the image before it is treated by this model. These processes will typically consist of parallel operations which can be efficiently applied to filter the raw image for enhanced input to the higher processing levels. Adaptive filtering strategies for this purpose, as suggested by signal detection theory, are the natural result of the preprocessing methodology introduced in the previous section.

Five major subtasks in our framework for picture processing must be expressible in terms of the model:

- Determination of primitive cells.
- Determination of properties or attributes of cells.
- Determination of relations between adjacent cells.
- Extension to relations between groups of cells or non-adjacent cells.
- Transformations to composite cells or cell merging.

This order is preserved in the discussion below.

2.4.1 Cellular Mosaic Decomposition of the Scene

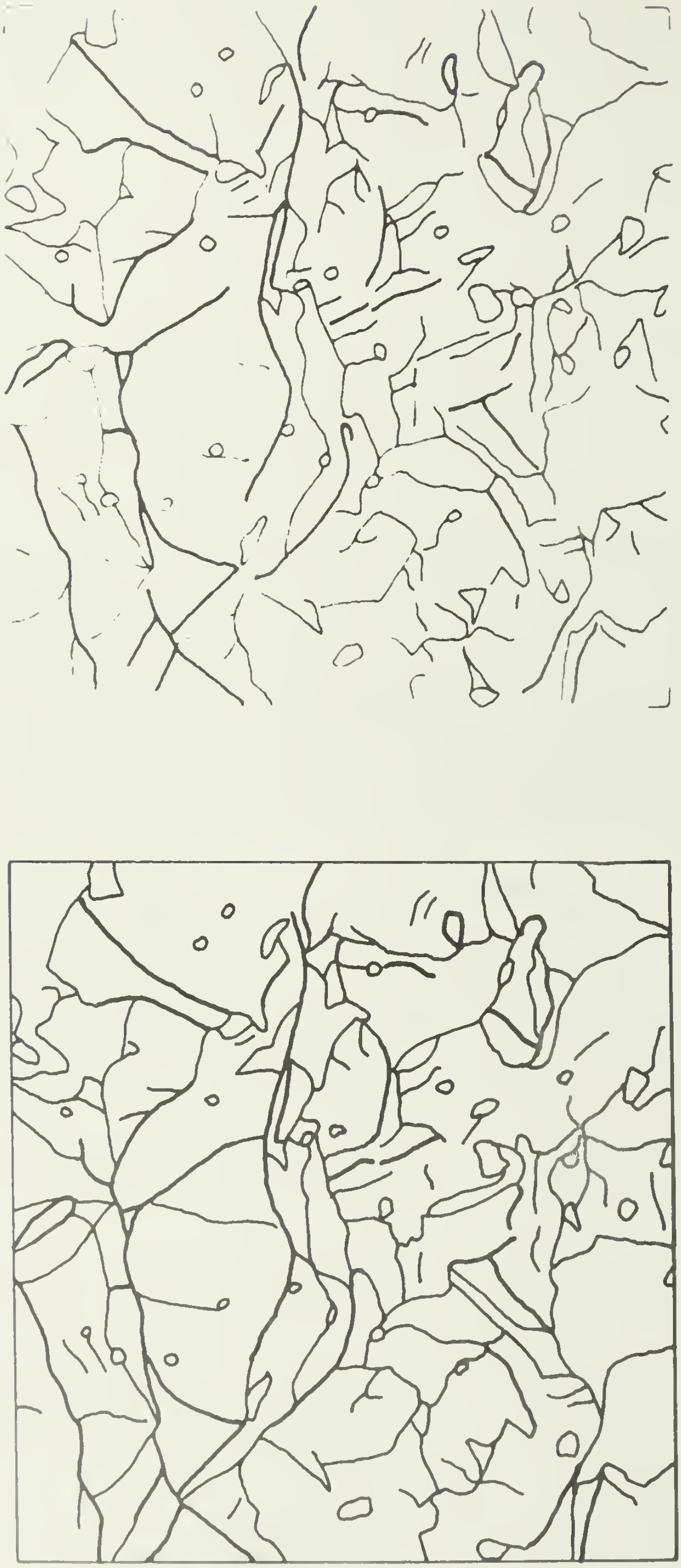
The model attempts to develop the structure and semantics necessary to treat a general two-dimensional scene. To achieve this goal, we introduce the first characteristic of the model. The picture is initially mapped into a cellular mosaic:a decomposition of the scene into regions bounded by simple curves (cells), which then form primitives for further analysis. (Figure 4). The choice of primitives strongly influences the development and the capability of the model. Cells seem to be far superior to primitives consisting primarily of line-elements, which were used in earlier approaches. Line-elements were often chosen to attempt to obtain a model based on one-dimensional and context-free grammars, which are inadequate in many cases.

After the articulation of the picture into cellular regions, spatial relationships and adjacency relationships can be conveniently expressed. Varying levels of attention can be applied to different regions by the choice of cells.

The determination of cells does not follow directly from edge or line detection. Regional attributes, such as texture, are important features for cell selection. Since many choices for cells usually exist, strategies to resolve the ambiguity must be found. It is our hypothesis that most two-dimensional patterns will be amenable to an initial cellular articulation strategy.

2.4.2 Graph Representation

The second characteristic of the model is the abstract relational graph representation used at most higher levels of the process. The structural



Cartoon and Cellular Mosaic Decomposition

of Ceramic Fracture in Figure 1

Figure 4

model allows arbitrary binary relations between items. This facilitates recognition procedures based on graph transformations.

An important class of procedures forms objects in a "name-independent" manner, i.e. without having to match each element to an explicit named prototype. These procedures can choose appropriate graph transformations given relevant properties of the relations between items.

This class of procedure will be used in the lower levels of analysis in order to increase the efficiency over a linguistic driven analyzer.

2.4.3 Composite Formation

The graph representation is chosen for global level picture processing. This level of generality is needed to express the many different and complex relationships among sub-elements of a picture.

The recognition process can then be viewed as replacement rules operating on graphs. This process, which is analogous to parsing, is called "composite formation". A replacement rule forms a composite element from sub-elements of the graph (Figures 5-6). The new graph formed by new composite elements and new relations involving these elements is then the candidate for further composite formation. For successful recognition, this process should tend toward a "recognizable graph", i.e. a graph which has somehow been specified as an acceptable goal.

We visualize the structure of this process as a three-dimensional tree where graphs form planes, or sections, at various levels. Composite forming graph transformations operate between levels. At the highest level is the root of the tree which represents the final composite recognizable graph.

2.4.4 Structural Component

To carry out the processing steps we introduce three spaces which parameterize the operations of the model. These are the event space, the structure space, and the data base. One of these, the structural ingredient, is discussed below.

The structure space provides the means for defining the form of an input picture which is capable of being successfully processed. Its analogy in string processing is the grammar of a language.

Figure 5. Crystalline Ceramic Fracture, Aluminum Oxide

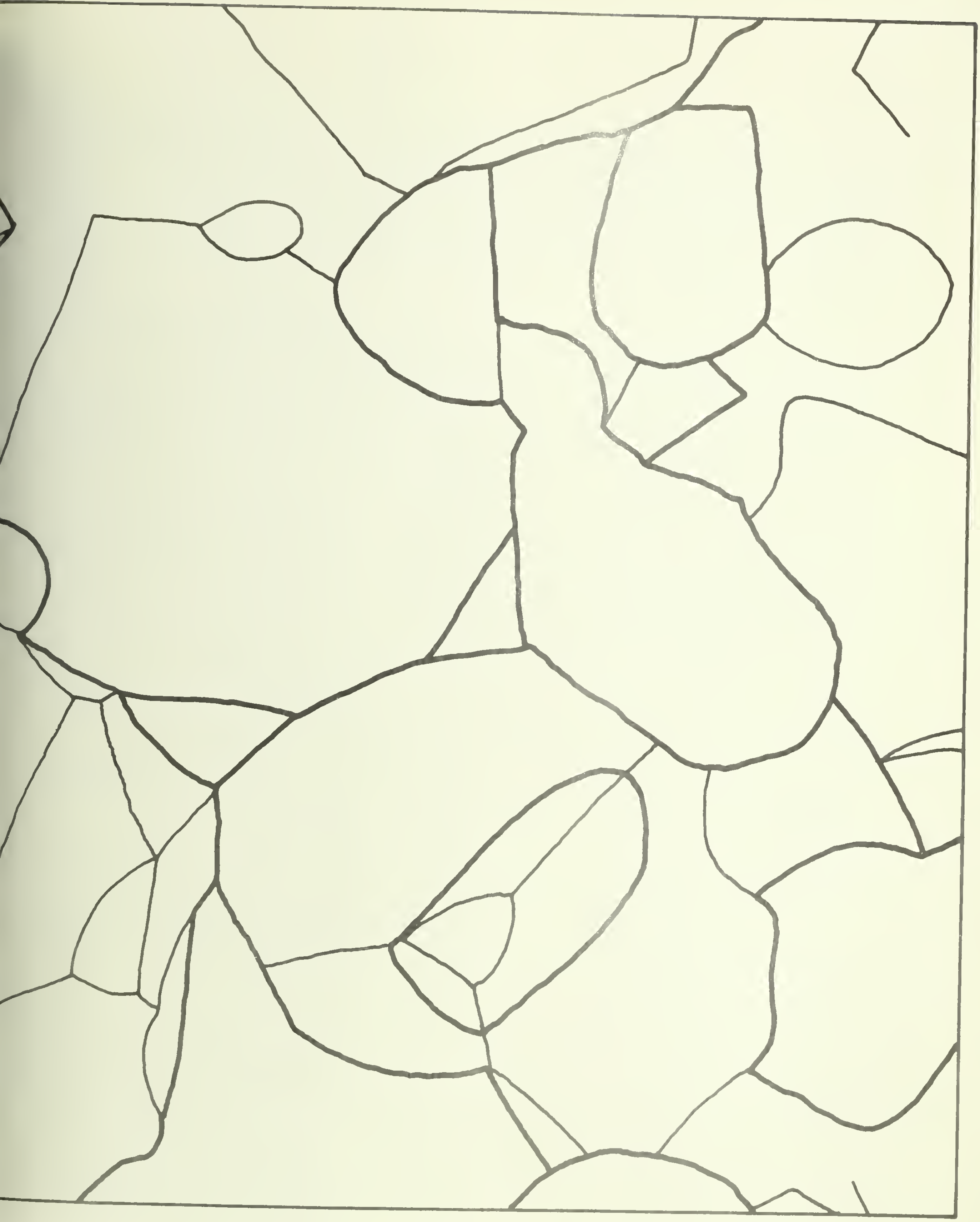


Figure 6

COMPOSITE FORMATION
Composite cells (wide lines) are formed from the initial cellular mosaic (thin lines) of the picture in Figure 5.

Lower level graph transformations operate entirely within the boundaries of the composite cells.

In order to achieve the major steps for two-dimensional picture processing, the structure space must be capable of representing hierarchial structures of elements with attributes and interrelated by binary relations. A structure is built up by applying set-replacement rules, a generalization of grammatical productions. Predicates are used to specify when a rule may be applied.

The advantages of associating semantic attributes as integral parts of grammatical rules have been treated by Knuth[24] for the case of context-free string grammars. Knuth claims that having attributes and attribute value assignment functions associated with each rule allows the constructs of the language to be defined in terms of their "immediate environment" and minimizes the interconnection between definitions of different parts of the language. In the same spirit, in the two-dimensional case, we also associate predicates with each set replacement rule to specify the necessary relations between elements.

It would appear that in picture processing the appropriate set-replacement rule for composite formation is largely inferred from such information as the attribute values of its constituents. Inference rules using Baysean strategies and subjective probabilities of Ward Edwards[40] -- in fact all the armamentarium of classical pattern recognition theory will be developed for this latter purpose.

2.5 Experimental Tests of the Model

To test the feasibility of the global model for picture processing, we plan to show a practical example for a small class of pictures in at least one application area.

At present the proposed application area is scanning electron microscope pictures, such as those of polycrystalline materials, which display a high degree of structural organization. These pictures exceed the complexity of simple line patterns. At the same time, they are not familiar scenes in which it is very difficult to separate the part of the recognition task which depends on the inherent visual structure from the part which has been learned from experience.

2.5.1 Picture Input

The initial input is an encoding of the original picture into basic sets. These can include lines, textured areas, and regions with attributes. Sufficient preprocessing is assumed, so that the next higher logical organization of the basic sets are cells.

2.5.2 Mosaic Determination

The input data is partitioned into the cells of the initial mosaic. From the edge and neighborhood information it will in general be necessary to imply the complete boundaries of the mosaic cells. Here the factors that make up a good mosaic must be determined.

2.5.3 Relation Determination

The relationships among subparts of the picture which are important to composite formation must then be determined. The structural composition of the picture should be expressed in terms of these relationships.

2.5.4 Composite Formation

The capability of fitting partitioned objects to named prototypes is necessary.

To this end composite formation will be attempted by applying graph transformations to relation-linked cells. Sufficient information must be maintained from the lower level relational parsing to match with a defined prototype. The attributes, relations and structures must also be considered with respect to the efficiency of alternate matching techniques.

It may be that grammar directed parsing rules can be defined equivalently in terms of name-independent graph transformations so that both techniques are interchangeable. Efficiency considerations will influence the interactions between these levels of parsing. At the levels where equivalences exist between grammar-directed techniques and relational techniques, factors to select preferred methods should be identified.

2.5.5 Specification Matching

To check the validity of the processing, the composite object identified must be matched to a specification which formed part of the input

scanning instructions and the associated training set. The fact that a composite was formed does not guarantee that it will be constituent of an optimal or even a successful parse (scene description). There will be ambiguous choices for objects at this level which must be further resolved. Decision factors for optimal choices must be determined.

2.5.6 Performance Measurement

To compare and evaluate the decision strategies which guide the parse, measures of efficiency must be recorded. The time, as well as other measures of the use of attributes, relations, and rules will be recorded for each strategy. We will attempt to identify the relevance of subparts of the proposed model and compare the capabilities of each feature. For example, the use of an available attribute, such as color, may greatly increase the efficiency of the process.

2.6 Related Work

2.6.1 Linguistic Models

Many picture processing systems whose chief component is a language for defining structures have been reported in the literature. Most of these systems deal with lines as terminal elements and use specialized cases of the general set-replacement rule mentioned under the structure space description. The systems of Anderson[1], Evans[11], Feder[13], and Shaw[37] conform to this description.

These systems fit the general two-level model of Miller and Shaw[29]. Pictures are described by a low-level primitive or terminal element description, supplemented by a hierarchic description which describes how primitives are grouped into higher level structures. Semantic components, such as variables, may be associated with a primitive or an hierarchic description. The hierarchic description is defined by a generative grammar which is then used to parse a given picture.

Two limitations of present systems are inefficiency and a line pattern orientation. The general inefficiency is due to the fact that the set-replacement rules are implemented by top-down exhaustive set-partitioning techniques which are inherently slow. Many candidate replacement sets exist

for each rule and each of them must be checked for the proper relationships and attributes before attempting a replacement.

Name-independent techniques attempt to do partitioning in a more efficient manner. Properties of relations basic to a class of objects may be needed to improve the partitioning for that class.

2.6.2 Data Base Models

In the "world model" for scene description being developed at Stanford[31], prototypes and instances of objects are defined in terms of attribute, object, value triplets. Here prototypes correspond to elements of our structure space and instances to objects in the data base.

Attribute-value pairs seem to be a convenient terminal representation for data elements. Hsiao and Harary[20] use this as a basic notation to define a formal system for information retrieval from files.

2.6.3 Heuristic Systems

The program of Guzman[17-18] demonstrated the feasibility of what we have called name-independent parsing of objects. Heuristics involving object vertices were used to merge objects. We have been able to show that Guzman's work is conveniently expressible in our proposed model. In this case, planar faces form the basic cells, and vertex types imply relationships between cells. The composite formation process of cell merging can be implemented by simple graph transformations with two classes of relations.

2.6.4 Non-Linguistic Models

Fennema[14] has formulated "a region-oriented structure" to represent scenes. He proposes merging equivalent connected points to elementary regions and then further merging under additional criteria. These criteria should be expressible by relations between cells.

3. PLANE PARALLEL PROCESSING STRATEGIES

An image processing strategy to be effective must also be computationally efficient - a criterion which can only be evaluated in the light of given image processing hardware. It is our intention here to devise, implement and evaluate parallel processing strategies appropriate to the Pattern Articulation Unit of the Illiac III Computer.

Specifically we recall that a picture with an extended gray scale range is commonly encoded over a regular raster of unit cells. This array of digitized scalar light intensity values can be conceptually viewed in two complementary, if equivalent, ways. In the first, or conventional <u>cellular representation</u>, the encoded picture is viewed as a matrix of digitized values (typically of uniform 1, 2, 4 or 8 bits per cell). Alternatively we can view the image topographically as planar sets of all cellular positions having a gray level amplitude $\geq$ the assigned (planar) threshold value. (See Figures 7-8). The <u>planar representation</u>, which has recently enjoyed new popularity, forms the basis of the PAX picture processing language and the Pattern Articulation Unit of Illiac III. (PAX was originally introduced as a simulation language for the PAU.)

Conceptually the planar representation emphasizes planar sets of cells having a common gray level. As the mesh size approaches zero, the asymptotic properites of the representation are treated in the measure theory associated with the Lebesque integral (in 2-dimensions). The conventional matrix representation finds its counterpart in the Riemann integral with its cell-by-cell identification of gray level. Preprocessing filters in the planar representation are typically homogeneous boolean transforms of the surround (both neighboring cells and neighboring planes) of each picture point. For scalar arrays, linear transforms with/without thresholding are more commonly used.

With this preamble we observe that i) little formal theory for the design of preprocessing (image enhancement/edge detection) filters using the planar representation has been developed to date, and ii) there are at least three classes of images for which these procedures are known to be effective--and warrant formal development. We propose to rectify both points i and ii.

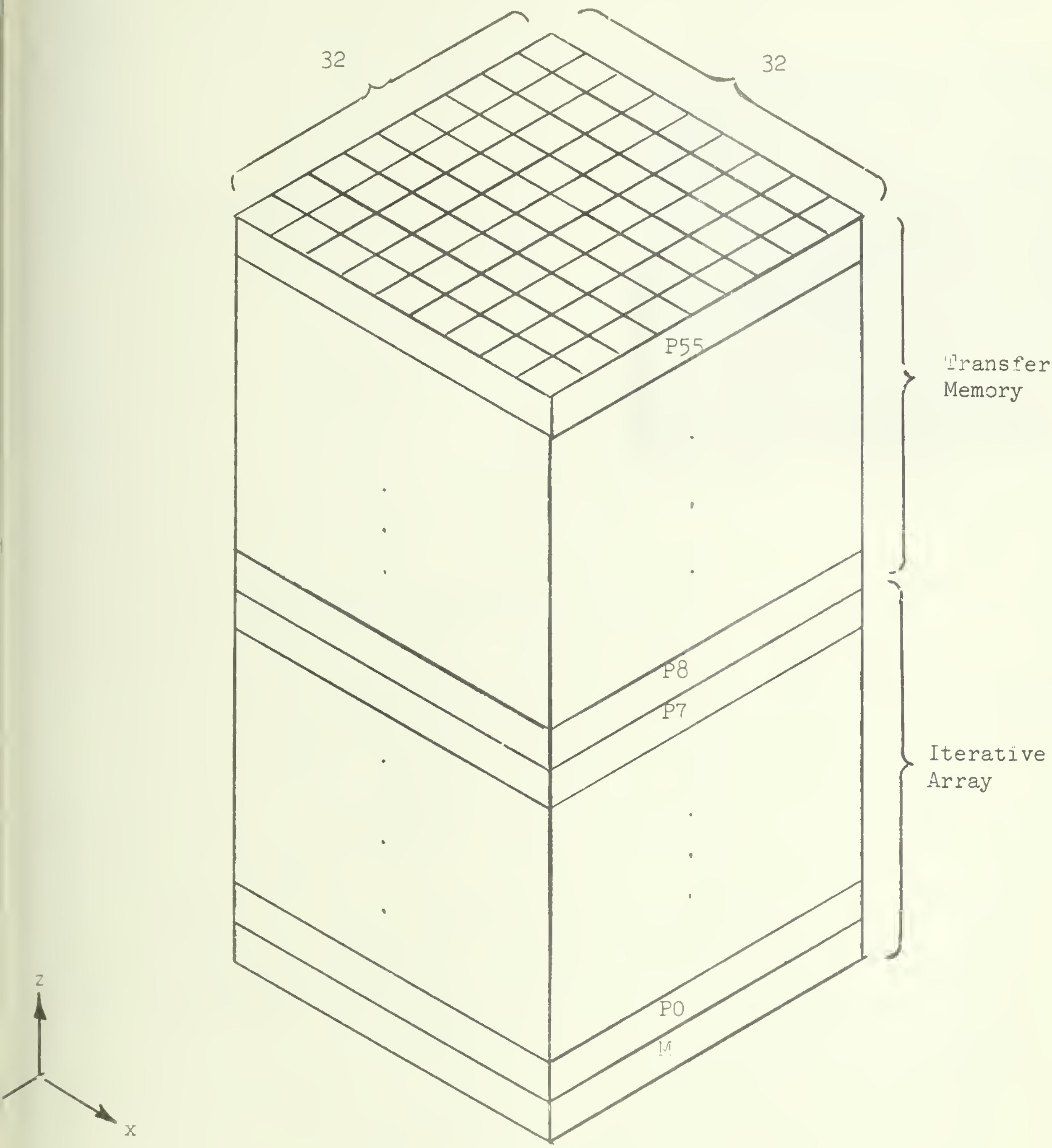
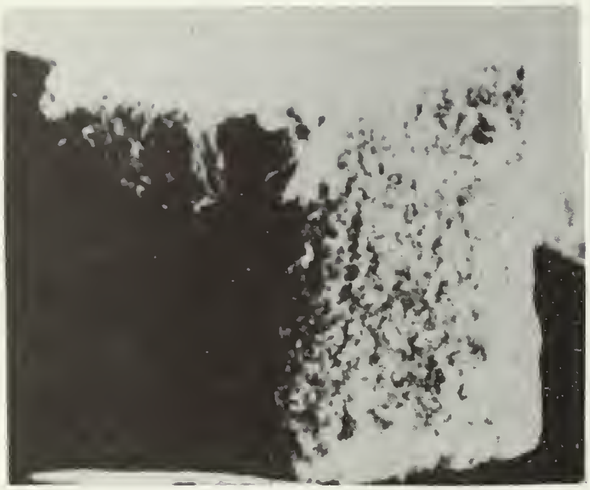
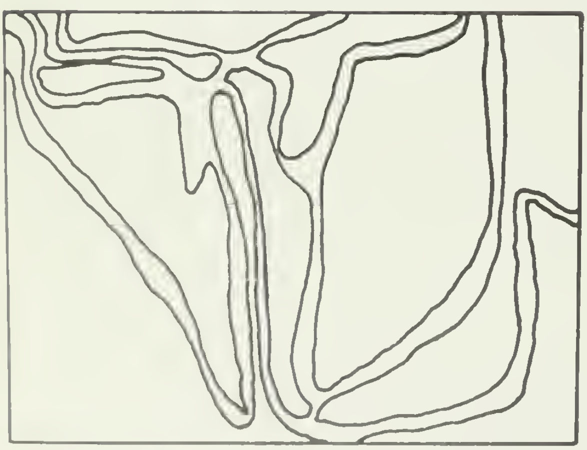


Figure 7 Planar Organization of the Pattern Articulation Unit



[illegible]EM of NaCl Crystal



[illegible] Intensity Contour Lines

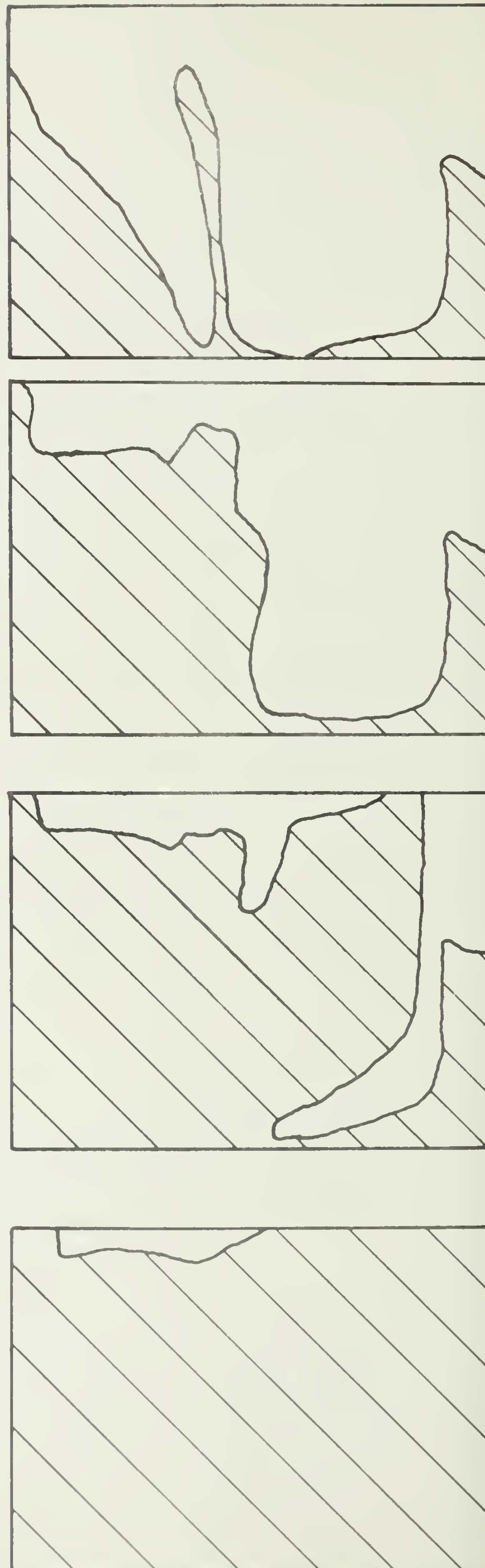


Figure 5

[illegible] Thresholding a

[illegible] Four Intensity

[illegible]

Areas of advantageous application for plane parallel processing includes the following:

1) Shape determination from scenes of shaded objects. Shading implies the orientation of each differential surface element. Different physical laws, however, apply to the reflection of light as opposed to (for SEM pictures) the emission of secondary electrons. Given an object with gradual variation of shading, the task is to find a suitable cellular decomposition, and to infer from this mesh a computer-graphics type representation of the spatial structure of the shaded surface.

2) Fast articulation of (quasi) line-like images. Fast tracking algorithms will be sought for patterns characterized by simple lines with/without noise. Suitable classes of pictures includes engineering drawings, nuclear tracks, chromosomes and Golgi-stained brain tissue.

3) Detection of differential changes in scene representation with motion. The important application of image processing to cine-photography and television is obviously predicated upon the development of strategies which detect incremental change in the cellular mosaic representation of the scene over time. Techniques are of interest here which avoid ab initio analysis of each frame and therefore exploit perserved or translated features.

It is the intention of this proposal to investigate these plane parallel strategies for image processing, to seek where possible formal methods of more general applicability and to quest for their earliest implementation within the Pattern Articulation Unit of the Illiac III.

4. LIST PROCESSING IN TAXICRINIC PROCESSORS

4.1 Function of the Taxicrinic Processors

The Taxicrinic Processors are the central control units of Illiac III. The Taxicrinic Processors are primarily responsible for the execution of user programs, that is, to oversee the operations of the Pattern Articulation Unit, the Arithmetic Unit and to initiate input/output operations in the I/O Processors by making requests to the Interrupt Unit.

The principal activity of a Taxicrinic Processor is the manipulation, search and systemization of abstract graphs (bilateral list structures) which have been produced from the pictorial input to the Pattern Articulation Unit. The name "Taxicrinic" comes from two Greek words: <u>ταξισ</u> meaning "arrangement" or "pattern", and <u>κρινω</u> meaning to "judge", thus indicating the TP's general purpose, which is to syntactically analyze digitized pictures and other material which can be cast into the form of a directed, labeled graph.

4.2 Design Features

The Taxicrinic Processors can address operands in either a paged or unpaged (contiguous storage) environment. Automatic reference to the Segment Name Table insures that operands are always referenced in a completely relative (relocatable) manner. Pointer stacks are provided to expedite addressing of trees (i.e. "structures" in PL/1 notation) and to permit automatic nested macro calls (see below).

Central to the design is the capability of the TP to execute a class of procedure calls (and returns) entirely in hardware -- including the mapping of actual onto formal parameters (operands). This facility means that i) extensive use can be made of read-only memory -- of particular advantage in a time-sharing system, and ii) an interpretative translation procedure can be used efficiently to implement, for example, an extensive list processing repertoire.

List processing has also been designed into the processor by including instructions for the control of Available Space, and for the insertion/deletion of a list cell.

In addition the TP must interpret Pattern Articulation Unit instructions, much as a more conventional CPU must communicate with an Arithmetic Unit. Where possible operand transmittal has been based upon buffering in the Operand Stack of the Taxicrinic Processor, an array of 32 bytes of fast storage with automatic refill/unload facilities coupling to that portion of the stack in core.

4.3 Proposed Investigation

The Taxicrinic Processor design was in part the outgrowth of examining a number of list processing languages and searching for that structure which seemingly offered notable advances over current machine organizations. Besides the explicit list processing instructions, of central importance here is the built-in macro facility whereby macro calls (and returns) are given hardware implementation. In the interim however the TP design has developed a life of its own as one sought an internally consistent hardware structure. During this same period available list processing languages have also evolved, although disappointingly few new developments such as the introduction of ring structures have emerged.

It is now proposed that concurrent with final checkout of the TP, the appropriateness of the TP as a vehicle for the implementation of list processing languages be reevaluated. We reiterate: our immediate interest here is not in the design of yet another list processing language (e.g. LISP, SLIP, SNOBOL 4 for lists and GRAIL for ring structures). Nor is our immediate interest, at this time, in the full implementation of these languages. Rather we wish to investigate the match between the machine (i.e. TP) and this class of language: can short efficient implementation be given to specifically list processing portions of these languages. In other words we are driven by the following questions:

1) Are the hardware instructions of the TP logically consistent? Do they steer their way gracefully through the seemingly endless interrupts of page out, available space empty, operand stack overflow, etc.?

2) Does the TP, appropriately scaled for circuit speed, fulfill its promise of providing a significant speedup in the execution of the core macros of contemporary list processing, and

3) Can a simulation model be developed that monitors the internal machine data transfers in a more global way and allows one to look for possibly more efficient machine organizations for list processing?

5. APPLICATIONS

5.1 Task Environment

Several considerations enter into the choice of an appropriate domain for the imagery of the scanning robot: 1) The projected application warrants the development of a practical scanning tool; (2) The characterization of the image as a limited number of regions and edges (i.e. cellular mosaic) must be natural to the image domain; and (3) The objects to be described are adequately complex, and yet are not overburdened with non-visual organization. Specifically scenes from daily life impose additional difficulties in this later regard.

For these reasons, and because of its potential significance for large scale integration, we have chosen to emphasize Scanning Electron Microscope pictures. Both in its applications to materials science and to histology and subcellular biology, the SEM offers an exceptional tool to explore a world only recently revealed. In addition recent advances give promise of direct readout of molecular and pauciatomic structures.[1,2,3]

And if robotics seems inappropriate to this macromolecular domain, let me quote Fernandez-Moran[4]: " - in a deeper sense we realize that electron microscopy represents the ultimate direct extension of eye and hand. Man may hereby be granted strange new freedom and capabilities of "seeing" and "doing" in those pivotal microcosmic domains of life which are still beyond mind's grasp."

Further, the Scanner-Monitor-Video of Illiac III Computer System could be readily expanded to incorporate an SEM as yet another "scanner". It

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[1] A.V. Crewe, "Closing the Gap - A 5Å Scanning Microscope", Twenty-Seventh EMSA Meeting, Claitor's Publishing Division, Baton Rouge (1969), pp 6-7.

[2] ________ and J. Wall, "High Resolution Scanning Microscopy", ibid, pp. 172-173.

[3] ________ and J. Wall, "Scanning Microscopy of Thin Biological Specimens", ibid, pp. 48-49.

[4] Humberto Fernandez-Moran, "Electron Microscopy in the Future", Twenty-Fifth Annual EMSA Meeting, (1967).

is proposed here however to concentrate on image description strategies which could be evaluated from film images. The loss of flexibility and the ability to readily interdigitate with the three common modes of SEM operation: emissive, conductive and luminescent, can be compensated by a later direct access to an SEM, should the scanning strategy discussed below prove applicable.

As implicated above the SEM provides an extraordinarily versatile tool for the examination of large scale integrated circuitry. Not only can one monitor the detailed geometry of the diffusion and deposition processes but under suitable operating conditions the local circuit fields can also be monitored. Checkout of developmental LSI circuitry of the future will likely entail the use of an electron beam probe (i.e. the scanning electron microscope) quite as today the technician uses a manually positioned contact probe. Visual models of the circuit terrain can be derived from the description of the multiple masks controlling the etching process. The visual models here could, for example, be expressed in the computer graphics package that has been developed here under the AEC computer graphics program. Image recognition as applied to SEM pictures or integrated circuitry then complements these computer graphic strategies, and provides a mechanism for this laboratory to remain abreast of the developments in large scale integration: a field of critical importance to future trends in computer architecture.

5.2 Two-Dimensional Scene Analysis

Before moving immediately to the full complexities of the 3-dimensional world of the SEM, it was felt that a better initial strategy would be to practice the problems of cellular decomposition on materials ideally suited for this purpose: typical microstructures encountered in optical metallography. Accordingly a graded sequence of 2-dimensional metallographic sections of increasing difficulty have been chosen (see Figure 9)*. For picture A (simple grain boundary contrast) typical parameters sought include mean linear intercept, grain section size distribution, anisotropy and aspect ratio. For picture B (simple particle distribution) parameters desired include

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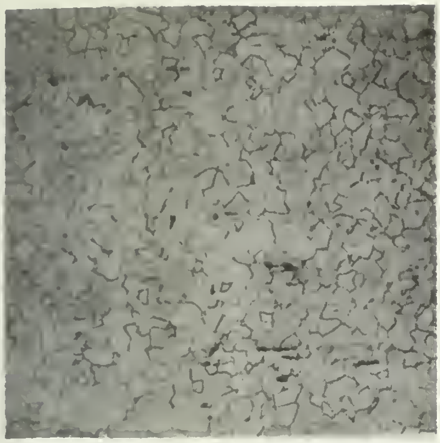
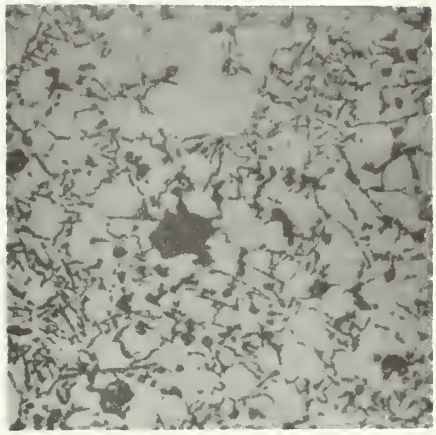
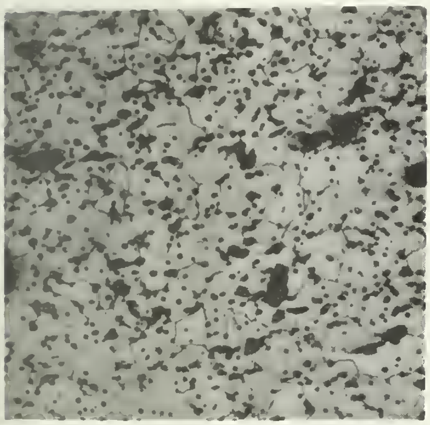
* These optical micrographs were selected for us by Mr. John B. Woodhouse of the MRL scanning electron microscope facility.



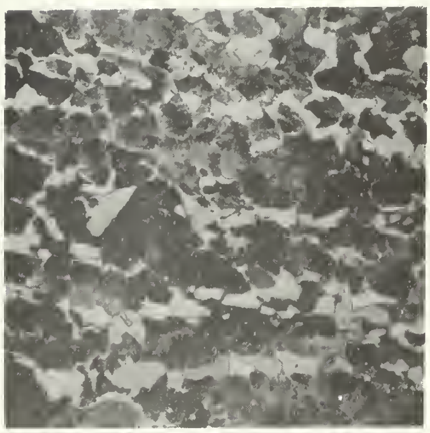
A. Simple grain-boundary contrast



B. Simple particle distribution



C. Particles in matrix with grain boundaries



D. Two phase sample with one phase having a gradation of tones

ain contrast only
(color discrimination suppressed)

F. Multiphase sample
(color discrimination suppressed)

Figure 9. Typical Microstructures Encountered in Optical Metallography

particle mean area in section, size distribution, anisotropy and aspect ratio. These first two images are currently interpretable by the quantimet analog image processor, and hence present a realistic lower bound upon the demanded capabilities of the proposed image processing system.

A second class of 2-dimensional scenes are presented by large scale integrated circuits, as seen under the light microscope. Again the limited depth of focus of the light microscope projects the intrinsically 3-dimensional circuit scene onto the image plane. Directly applicable here will be algorithms for the fast articulation of line-like images (see Section 3, topic 2).

Finally to explore the possibilities for detecting differential changes in scene representation with motion (see Section 3, topic 3), we propose to explore time-lapse cinemicrophotography. Specifically we have in our possession[1] elegant films of the locomotion of cancer cells in vivo compared with normal cells in the rabbit ear chamber. Here of course the "cells" of the mosaic scene decomposition are largely biological cells: lymphocytes, granulocytes, macrophage, monocytes, fibroblasts and cancer cells.

5.3 Three-Dimensional Scene Analysis

Typical SEM micrographs are exhibited in Figures 10-12. In the first scene dendrites of a ferritic material have been vapor deposited some distance from the melt. Note how the four faces on each dendrite (the pyramids) are parallel. Magnification here is 2000X.[2] Both in this image and in the second micrograph[3] of mangonese oxide crystals the analogy with the idealized scenes of blocks, as treated by Guzman, is readily apparent. And intentionally so, for here we can reasonably anticipate some measure of success with the picture processing model.

These latter micrographs also provide exemplar images to practice the remaining plane parallel processing algorithms of Section 3: shape

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[1] Courtesy of Professor Sumner Wood, Jr., Department of Pathology, John Hopkins University.

[2] Courtesy of H. S. Sandhu and R. Harmer. Micrographs taken by J. Temple Black, Center for Electron Microscopy, University of Illinois, Urbana,

[3] Courtesy again of J. Temple Black.

gure 10. The Melt Interface of a Silica Brick From an Open Hearth Furnace (see text)

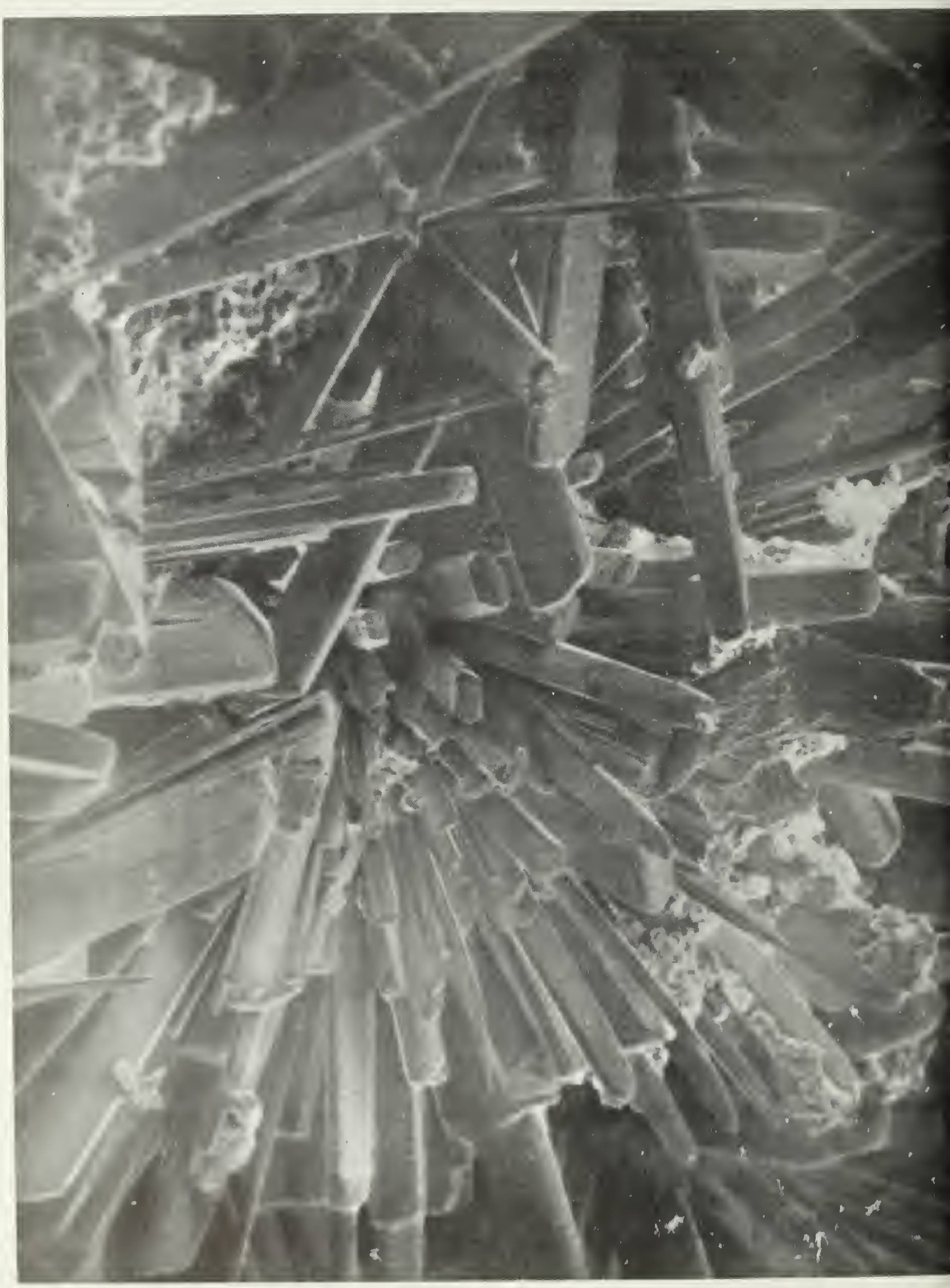

Figure 11. Manganese Oxide Crystals with Metallic Silver Precipatate

determination from scenes of shaded objects. This situation is very characteristic of the repertoire of less complex SEM pictures.

Finally Figure 12, Radiolaria 900X by Phil Sandberg, is introduced to show the extensive depth of field in the SEM. Given stereo pairs of SEM micrographs, it is possible to use photogrammetric techniques to compute absolute dimensions of all member parts. We shall, however, leave this task for a later time.

Courtesy of J. Temple Black, Center for Electron Microscopy, University of Illinois, Urbana.

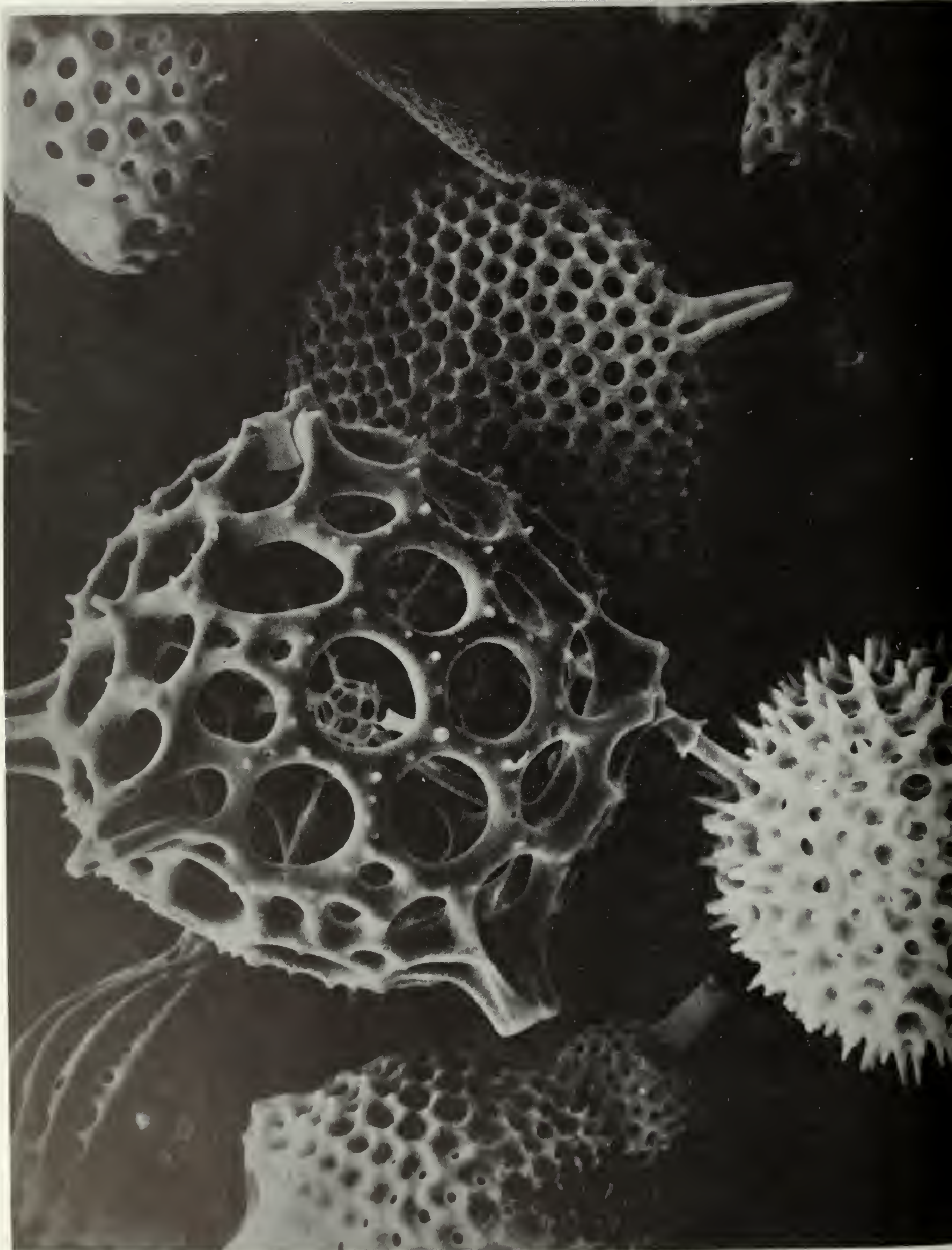

Figure 12. Radiolaria 900X by Phil Sandberg

6. FACILITIES AVAILABLE

6.1 Scanner-Monitor-Video System

The Scanner-Monitor-Video (SMV) system of Illiac III provides a general purpose, high resolution scan/display facility. Rasters of all formats prescribed in the SJCC article ("Parametric Description of a Scan-Display System", by L. A. Dunn, L. N. Goyal, B. H. McCormick and V. G. Tareski, Spring Joint Computer Conference 1969; Appendix 2) are now operational. In addition, the intermachine link between the core memories of Illiac III and the PDP-8 computer of Professor C. W. Gear's graphics group is also operational.

For prototype studies with the SMV scan/display system a general purpose program (SEP) has been written[1]. This program, designed by R. T. Borovec, includes routines to edit scan parameters, run the scanner, read and write digitized pictures on DECTAPE (for subsequent processing on either the PDP-8 or the 360/75 running PAX), print gray scale pictures and check the integrity of the various hardware links. All commands are issued through a TTY terminal.

We have been very pleased with the linearity and reproducibility of the rasters, the quality of the gray scale encoding (currently limited to 16 levels) and the high data ratio (5 MHz bit rate output). The 2-1/2 years of intensive analog circuit design work (largely by Divilbiss and Franco) is now proving to have been a worthwhile investment. Comprehensive hardware documentation is also being prepared. The extensive control of the SMV system uses 7400 Series dual inline packages, and could be readily copied at other AEC installations.

Currently we are evaluating the SMV system by looking at applications to polycrystalline materials research, exfoliative cytology and the scanning of brain nuclei.

6.2 Illiac III Computer System

Illiac III is an experimental computer being designed and constructed by the Department of Computer Science as a first instrument to explore the potentialities of high speed image processing. Concurrent with the computer design work, the AEC contract AT(11-1)-1018 has supported research into the theory of image processing.

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[1] Richard T. Borovec, The Illiac III Scanner Exerciser Program (SEP), DCS File No. 830, April 1970.

The Illiac III Computer System can be described in terms of 14 constituent subsystems of processors, units and peripheral device groups as follows (see Appendix 1, Figure 1):

i) Central System (6 subsystems)
ii) I/O System (3 subsystems)
iii) Peripheral System (4 subsystems)*
iv) Power Distribution System (global to all subsystems).

Only two, the Fast Core Storage Units and the Low Speed Terminal Network, are of commerical design. The other constituent subsystems have been designed almost entirely as part of the graduate research program of the Department of Computer Science.

This massive design/development program was not undertaken lightly. Rather, central to the contract program has been the study of the computer architecture appropriate for high speed image processing. These peripheral devices, units and processors must be able to talk to one another--and with minimum data format conversion: the Scanners feed the Pattern Articulation Unit, whose output in turn is interpreted by a Taxicrinic Unit. This global integration of the design has been costly but integral to the integrity of the system design.

6.3 Scanning Electron Microscope Facility

The AEC-supported Materials Research Laboratory of the University of Illinois, Urbana, is setting up a new facility for electron microscopy. A JSM-3 Scanning Electron Microscope, Japan Electron Optics Laboratory Co., has been purchased and is now being installed in the laboratory.

This facility will be under the direction of Mr. John B. Woodhouse, who has formally offered us full cooperation. Mr. Woodhouse has prior industrial experience in the design of analog instruments for metallurgical and cellular image processing. He therefore sees the proposed computer-based image processing system as a natural next step. Our interface with the SEM facility will be Dr. Jerry Chih-li Chen, a solid state physicist now returning for a Ph.D. degree in Computer Science.

The proposed collaboration has been cleared with Professor Robert J. Mauer, director of the Materials Research Laboratory, and has his full support.

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*Includes Scanner-Monitor-Video System of Section 8.1. (Appendix 1).

7. PRELIMINARY INVESTIGATIONS

7.1 Properties of Relations

As a result of the composite formation ideas we attempted to do some theoretical work to determine general rules for composite analysis given a directed graph.

First, in DCS File No. 762[28], we studied basic set related properties of binary relations. These are properties such as reflexive, symmetric, transitive, and cyclic, which do not depend on additional structure on the set. We defined nine independent properties and showed that exactly forty consistent classes of property values existed. This characterization appears useful for any general relational or graph-oriented system for the purpose of reducing the complexity of graphs by eliminating redundant edges.

Usually there is some structure in the set of objects under consideration. For example, if a composite element is formed by the set union of subelements, then we can consider the power set of the set of basic objects and the structure is that of a Boolean algebra. In this case we would like to know how relations can be extended from constituents to composites, and classify relations according to types of composite formation properties.

Thus, in another publication[35], we considered systems of binary relations between latices where the meet and join operations established the basic structure. We defined thirteen properties of binary relations which depend on the lattice structures.

Further theoretical work in this area should involve a consideration of special types of lattices, such as modular and geometric. Each type of lattice will imply certain of the composite formation and relation extension properties. The goal here is to find the mathematical structure best suited to picture processing operations.

7.2 Graph Transformations

In order to implement name-independent procedures we would like to imply graph transformations from the properties of individual relations. In DCS Report No. 368[36], we considered a set of simple graph transformations which seemed plausible according to some previous experimentation, and determined which transformations were implied by the previously defined properties.

One useful concept for selecting preferred transformations is the idea of an information lossless transformation. Transformations which can be shown to be reversible, i.e. the transformation and its inverse are always valid, can be performed with no loss of information.

7.3 Structural Component

Our early formulation of structural description and structural operations (graph transformation) was expressed in the WEB language. The language arose from a need to describe separately, readily, and concisely, the essential logical, geometrical, and electrical characteristics of a contemporary digital processor in a form amenable to symbolic manipulation. The WEB logical block allowed the specification of structural levels in a manner which is very similiar to the NAPE (n-attaching point entity) used in the recent picture processing system of Feder[13] . The WEB blocks are now generalized to the set-replacement rules of the picture specification language.

7.3.1 Language for Picture Specification

A number of graphical or pictorial descirption languages have been studied to determine desirable features of an image processing language, and to evaluate for each language its satisfaction of stated a priori criteria.[34] After a brief survey of some of the most representative of these languages, a new image processing language ICØN was defined.

The ICON language can be reinterpreted as specifying set-replacement rule grammars. A rule, P_p, replaces a set of $\eta_p \geq 1$ elements by a set of one element. The rule may be represented by the diagram of Figure 13. Here the set $\{Xp1, Xp2, \ldots, Xpn_p\}$ is replaced by the set $\{Xpo\}$. Each element, Xpj, has an associated set of attributes, A(Xpj). A set of attribute mapping functions, $\{fpj\alpha\}$ determines the values of each attribute α in A(Xpj) from the values of attributes of the other elements. Sets of relations between the attributes of each element, $\{R(A(Xpj))\}$, and between all elements, $\{R(Xp1, Xp2, \ldots, Xpn_p)\}$, can also be specified.

The set-replacement rule and attribute assignments can be made if elements are found which satisfy all of the relations.

W. Bond et.al., "The WEB System, Part II: A Formal Description of the WEB Input Language", DCS Report No. 232, University of Illinois, June 19, 1967.

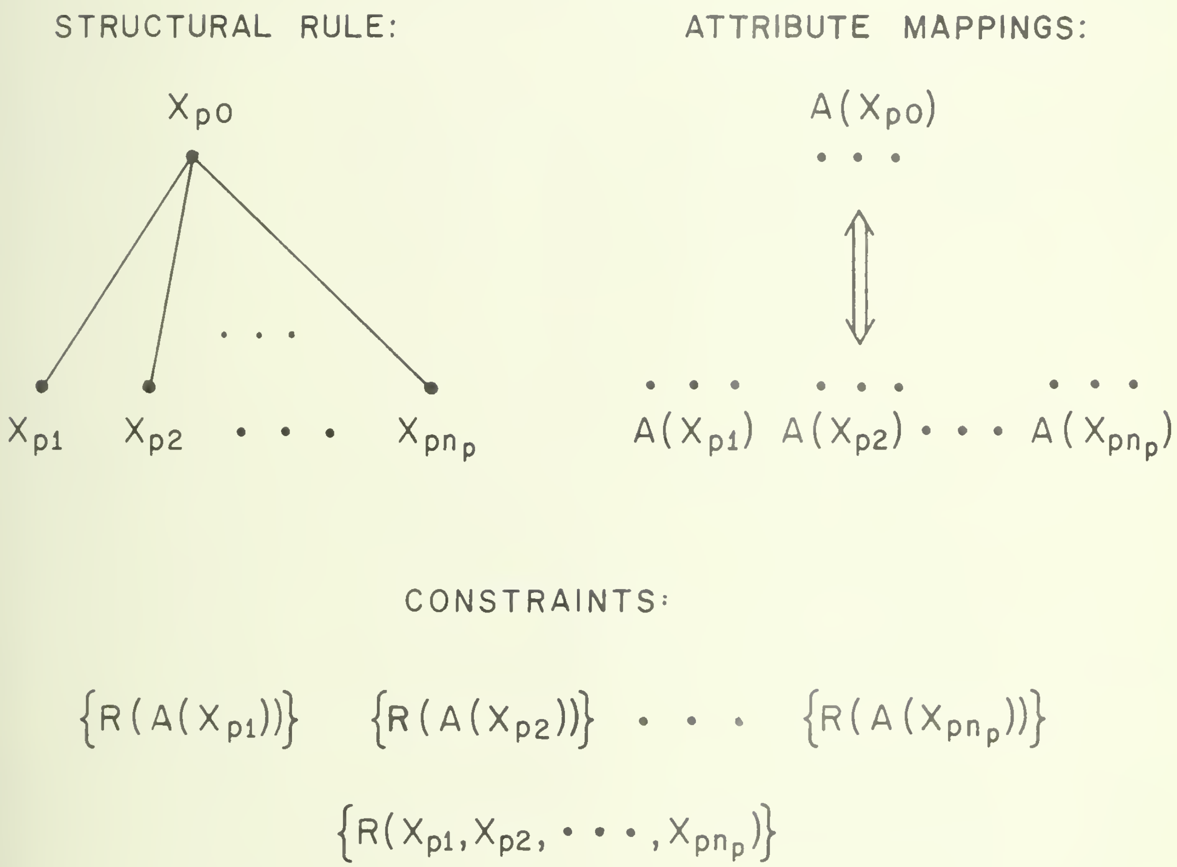

Figure 13. Set-Replacement Rule

7.4 Plane Parallel Processing

7.4.1 Picture Description

Much work, summarized and referenced in Narasimhan[1'], has been done on a descriptive scheme for classes of pictures based on labelling techniques using parallel processing algorithms. The structures of syntactic descriptive models was studied by considering their specific application to bubble chamber pictures. A program called BUBBLE TALK[2'], was designed for online conversation in the context of bubble chamber pictures.

7.4.2 Scanning Procedures

The Bubble Scan I program by Narasimhan[3'] was concerned exclusively with the scanning of one view of a bubble chamber stereotriad. Input-output features, data structures, and scanning procedures were implemented on the IBM-7094 computer.

7.4.3 PAX II

In the course of design studies for the Pattern Articulation Unit (PAU), it proved useful to introduce a programming language PAX, initially considered as a simulator for the PAU. This language introduced, we believe, the first systematic use of connectivity information in image analysis. The PAX concepts were systematized and extended in a series of basic papers by Narasimhan (than at this laboratory). The PAX language, as PAX II, has recentl been implemented for the IBM 360/75 by J. W. Snively, Jr. and E.B. Butt, formerly of the University of Maryland, and is used, for example, by Kirsch and Lipkin in their experimental studies of bio-medical image processing at the National Institute of Health. In addition PAX has been taught as the language for picture preprocessing and feature extraction in a recent commercial course on Image Processing by Cybex Associates, Inc.

In an effort to provide a bridge between the present IBM 360 simulation and the PAU hardware execution of local feature extraction algorithm, the Snively-Butt version of PAX II was adapted to the Illinois installation. Report No. 314, "The PAX II Picture Processing System at the University of Illinois," March 1969, edited by R. T. Borovec describes the translator.

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8. SUMMARY

Strategy is proposed to permit personnel (not trained in computer technology) to input scanning instructions directly to the image processing system.

To this end a formal model for picture processing is proposed. Constituents of the model include local preprocessing, partitioning of the scene into a cellular mosaic, clustering of picture sub-elements (initially the cells, or regions, of the cellular mosaic) into composites, and the matching of the hierarchial structure obtained to prototype objects.

Particular emphasis is placed in the proposal upon developing effective and efficient procedures for image analysis. Attention is given to signal detection theory (for edge detection/texture discrimination), plane parallel picture processing (for pattern articulation), and efficient machine implementation of list processing(to transform the graph representation of scenes).

Of the diverse applications discussed in the proposal, automatic photo interpretation of Scanning Electron Micrographs has been singled out for intensive investigation. The microstructure of objects examined in the SEM are intrinsically 3-dimensional. Polycrystalline and biological materials give rise to images with gradations of tone and texture. Such images hold a wealth of information which at present can not be extracted automatically. It is an aim of this proposal to rectify this situation.

Operational facilities of the Illiac III Computer System, in particular the S-M-V Scan/Display System, will be used in this investigation. It is foreseen that image analysis is now entering a phase of exuberant development comparable to that recently seen in computer graphics. Display algorithms of this latter discipline are now reappearing turned inside-out, so to speak, as scene analysis algorithms. It is appropriate therefore to now make these critical experimental probes toward a truly comprehensive image processing system.

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